A SEARCH FOR DARK MATTER USING CRYOGENIC DETECTORS (CDMS)

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The Cryogenic Dark Matter Search experiment uses germanium and silicon detectors cooled to cryogenic temperatures in a direct search for weakly-interacting massive particles in our Galaxy. The novel detectors allow a high degree of background rejection by discriminating between electron and nuclear recoils through the simultaneous measurement of the energy deposited in phonons (heat) and ionization. Exposures of a few kilogram-days from initial runs of our experiment yield (preliminary) upper limits on the WIMP-nucleon cross section that are comparable to much longer runs of other experiments. Current and future data promise significant improvement, primarily due to improved detectors and reduced backgrounds from surface radioactivity.

1 Searching for WIMPS

Observations of stars and galaxies over a large range of distance scales indicate that most of the matter in the universe is "dark," seen only through its gravitational effects,[1,2] and that much of this dark matter is non-baryonic and "cold."[3] The best model for producing observed structure in the universe over three orders of magnitude in distance scale has 20% hot dark matter, 5% baryons, and 75% cold dark matter, with critical mass density ($\Omega_m = 1$)[4]. Massive, stable (or long-lived) particles with weak-scale couplings, such as may exist under supersymmetry or other extensions to the standard model, could provide about the implied amount of non-baryonic cold dark matter.[5,6]

If weakly-interacting massive particles (WIMPs) exist, they would now make up a major component of the dark matter in our own galactic halo.[7] For a standard halo comprised of WIMPs with a Maxwellian velocity distribution characterized by $v_{\rm rms} = 270$ km/s and a mass density of 0.4 GeV/cm^3, the expected WIMP flux at Earth is enormous, $\sim 10^7/m_\chi$ cm^{-2}, where m_χ is the WIMP mass in GeV. However, expected WIMP-nucleon scattering cross sections less than 10^{-41} cm^2 imply rates for WIMP-nuclear scattering ranging from 0.001 to 1 event per kilogram of detector per day, and the expected recoil energy is as low as 1 keV.[6,8] Direct detection of WIMPs will require large detector mass, low energy thresholds, efficient nuclear recoil detection, and long counting times.

2 CDMS at Stanford

Thus far, WIMP direct-detection experiments have been limited by irreducible backgrounds, primarily photons and electrons from radioactive contamination or activation. New techniques are needed to actively discriminate against such backgrounds without losing efficiency for the nuclear-recoil signature of WIMPs. One method for achieving this is to cool semi-conducting crystals to cryogenic temperatures (< 100 mK), where it becomes possible to detect the heat (phonons) liberated when particles interact in the crystal. Since nuclear recoils are less ionizing than electromagnetic backgrounds, one can reject such backgrounds by measuring both charge and phonon signals.[9,10] Following a decade-long development effort, the Cryogenic Dark Matter Search (CDMS) collaboration[a] began running such detectors in a low-background environment at Stanford in 1996. Our early data runs yield preliminary upper bounds on the WIMP-nucleon cross section that are comparable to much longer exposures of other experiments, illustrating the power of this technique.

2.1 Description of the experiment

The primary tools of this experiment are novel particle detectors which operate at 20 mK. Key to the experiment is the simultaneous measurement of the energy ΔE deposited in a scattering event both in phonon-mediated (heat) signals and in ionization (charge). The ionization measurement is made by applying a small (a few V/cm) bias voltage across the two sides of the cm-thick semiconductor targets. Electron-hole pairs are collected efficiently throughout the bulk of the detectors, resulting in FWHM energy resolutions as good as 640 eV. The division of the surface contacts into an inner region and an outer region provides some information on the radial position of the scattering event. Unfortunately, trapping

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sites near detector surfaces result in a 10–30-μm-thick "dead layer" where charge collection is incomplete.[11] This makes the detectors vulnerable to surface contamination backgrounds, particularly from low energy electrons and photons. Recently, we have developed new ionization contacts which produce a much smaller dead layer, greatly reducing the effect of backgrounds at low energy. This technology will be tested on the next Ge detectors to be used at Stanford. If successful, it will be the basis for all future ionization contacts on both Ge and Si.

The CDMS detectors employ two distinct methods for performing the phonon-mediated measurement of the recoil energy ΔE. One technology uses two neutron-transmutation-doped (NTD) germanium thermistors eutectically bonded to a 1.2-cm-thick 6-cm-diameter 165-g cylindrical crystal of high-purity germanium. When the device is in contact with a 20 mK bath, monitoring the thermistor resistance gives the temperature rise $\Delta T = C^{-1}\Delta E$, where $C \sim 1$ keV/μK is the detector heat capacity. The resulting energy measurement has a FWHM resolution of 650 eV at 10 keV.[12] The use of two NTDs permits the rejection of events that originate in an NTD and would otherwise mimic the small ionization of a nuclear recoil. Implemented on Ge, we refer to this readout technology as BLIP.

The other technology uses quasiparticle-trap-assisted electrothermal-feedback transition-edge sensors (QETs) to detect non-equilibrium phonons before they have time to thermalize.[13] Tungsten meanders on a surface of a cooled 1-cm-thick cylindrical detector are held in the middle of their superconducting transitions by electrothermal feedback; a voltage bias V causes Joule heating (V^2/R), which increases at lower temperatures or resistances R, and decreases at higher temperatures. Deposited energy drives the tungsten towards normal conduction, producing a current signal. The time integral of this signal is proportional to the deposited energy, which is measured to 650 eV (FWHM) in our 100-gram silicon targets; the technology is now being transferred to germanium targets. Since the phonon collection time is fast (a few microseconds), relative-timing information from the four sensors on a device allows a two-dimensional determination of the event position to a few millimeters. Timing information also provides the ability to reject events on the top and bottom surfaces of the detectors, where the charge dead layer may otherwise compromise the detector discrimination capability. In our current implementation on Si, this technology is labeled FLIP.

Figure 1 shows the simultaneous phonon and ionization measurements for a 165 g Ge BLIP and a 100 g Si FLIP detector during gamma (^{60}Co) and neutron (^{252}Cf) source calibration runs. The plots clearly show the gamma/nuclear recoil discrimination capability of the detectors. The neutron calibration data show that the ratio of the ionization yield for nuclear recoils versus electron recoils is slightly higher in Si ($\sim 1/2$) than in the Ge ($\sim 1/3$). The relative ionization yield is not linear at low energies and, in general, must be measured as a function of recoil energy. The neutron recoil spectrum in Si is 2.5 times higher in energy than that of Ge from a similar incident neutron spectrum. This kinematic effect makes Si a good choice for measuring the neutron background and would allow us to measure the mass of incident WIMPs by comparing their spectra in Si and Ge. The discrimination for BLIP shown in Figure 1 corresponds to an effective gamma background contamination of less than 1% for recoil energies greater than 20 keV, with nuclear recoil acceptances of at least 99%. FLIP has much better background rejection (5×10^{-5} for recoil energies greater than 30 keV) due to the use of timing information, although the nuclear recoil acceptance is lower ($\sim 50\%$) at the present stage of analysis.

Figure 1: Scatter plots of the ionization measurement versus the recoil energy measurement for the 165 g Ge BLIP and 100 g FLIP detectors, obtained during ^{60}Co [(a) and (c)] and neutron [(b) and (d)] calibration runs at the Stanford Underground Facility (SUF). The ionization measurements are normalized to electron equivalent energy. The curves represent fits to the region of nuclear recoil events.

The remainder of the experimental apparatus consists of specialized low-activity detector-housing modules mounted in a shielded cryostat made from a set of nested copper cans. The cans are cooled by conduction through a set of concentric horizontal tubes extending in a dog-leg from a dilution refrigerator. An external, 15-cm-thick lead shield reduces the flux of background photons by a factor of $\sim$1000, while 25 cm of polyethylene shielding reduces the flux of neutrons by a factor of $\sim$100.[14] Samples of all materials internal to the shield are carefully screened in a low-background HPGe counting facility for radioactive contaminants. Further shielding close to the detectors is achieved with 1 cm of ancient, ultra-low-activity lead, which has a low concentration of ^{210}Pb, a beta-emitter. Due to the complexity of the detectors and cryostat, the first phase of the experiment is being performed at a shallow site at Stanford University at a depth of 17 meters water-equivalent (mwe). This overburden is enough to eliminate the hadronic cosmic-ray flux. However, the overburden reduces the cosmic-ray muon flux by a factor of only 5, requiring further rejection of backgrounds with a hermetic plastic-scintillator muon veto system. The veto efficiency for direct muon hits in the detectors has been measured to be 99.995%. The ratio of nuclear recoils in FLIP which are not veto associated to those which are veto coincident implies a lower limit on the veto efficiency for cosmic-induced neutrons of 99%.

2.2 Results

Several data runs have been taken in the low-background facility over the past two years, indicating that the experiment can successfully operate over months-long timescales with energy resolutions comparable to those of calibration data. The rates of photon and neutron backgrounds have been consistent with or less than the expected levels, confirming that our goals at the shallow site are attainable and that our screening procedures are effective in limiting these sources of background.

Figure 2 shows ionization energy versus recoil energy for events during part of the latest background run of two 165 g Ge BLIPs and one 100 g Si FLIP at Stanford. The main diagonal band in each case is from gamma events. The off-axis events just below the gamma band for the BLIP detector arise from the interaction of electrons, most of which were ejected from surrounding material by muons, in the surface dead layer of the Ge detector.

The population of events lying along the nuclear recoil line below 20 keV recoil is believed to be due to $\sim 10^6$ atoms of tritium on the surface of the Ge BLIP detectors. The smaller number of events ($\sim$ 10 per live day in the range 20-100 keV) at higher energies close to the line could be due to electrons emitted from surface contamination such as ^{40}K from accidental sweat contamination, or ^{137}Cs, ^{14}C, and ^{210}Pb from radon plating.

Ultimately, it is our intention to use the gamma calibration data in order to estimate the number of misidentified gammas that lie near to the nuclear recoil band in the muon anticoincident background data, and so subtract their contribution. However, at present the events

Figure 2: Ionization energy versus recoil energy in a 165 g Ge and a 100 g Si FLIP during low background running at Stanford after all cuts, including timing cuts for FLIP. Plots (a) and (c) are coincident with signals in the muon veto system, and (b) and (d) are anticoincident.

that appear in the nuclear recoil band in Ge BLIP background data sets are dominated by surface contamination. Given the overlap of the electron event distribution with the measured nuclear recoil region these events effectively constrain the nuclear recoil (dark matter) limit set from the BLIP data. Recent data from the 100 g Si FLIP have shown that the rise time of pulses produced by surface electrons is significantly faster than those from gammas and neutrons. Use of this timing information produces the much-cleaner background spectrum for the Si FLIP shown in Figure 2. These distributions also show clear evidence of neutrons produced by cosmics in the coincident data, but very few events in the nuclear recoil band in the veto anti-coincident set. Two events remain in the 30-60 keV energy range, where we expect 0.75 events from "punch-through" neutrons which originate outside of the muon veto.

2.3 WIMP Limits

The fundamental WIMP-nucleon cross section for coherent spin-independent elastic scattering allows direct comparisons between previous experiments and the preliminary and anticipated results of the CDMS experiment. Figure 3 shows the results of the first analysis of the latest sample of CDMS data using the 165 g Ge and 100 g Si detectors, together with recent limits from Rome NaI [15], UK NaI [16], Milan TeO_2 [17], Modane Al_2O_3 [18], and Ge diode [19] experiments. The CDMS results are preliminary and based on data that represent less than 7% of the total data anticipated from the experiment at Stanford. Above the Ge noise threshold of 2 keV total recoil energy, but below 18 keV, the Ge spectrum is dominated by backgrounds we expect to remove in upcoming data runs. Because the Si FLIP has additional rejection power against these low-energy surface backgrounds due to timing, it achieves better limits for low-mass WIMPs than does the Ge, in spite of the five-times larger cross section for WIMP-nucleon scattering in Ge. The current CDMS results are competitive with other existing limits because of the detectors' extraordinary capability to reject a large number of background events by simultaneously measuring ionization and thermal energy.

Figure 3: Existing limits set by previous experiments. The Ge diode limit is the envelope of the UCSB/LBL/UCB, COSME-2, Canfranc, and Heidelberg-Moscow experiments; the other published limits are referred to in the text. Also shown are preliminary limits from CDMS with a 100 g Si detector with 1.0 kg-d exposure and a threshold of 5 keV, and a 165 g Ge detector with 6.9 kg-d exposure and a threshold of 3 keV.

The data from the first CDMS data at Stanford have been encouraging, yielding both competitive dark matter limits and a deeper understanding of backgrounds. For future runs, improved cleanliness procedures, increased detector self-shielding, and the implementation of improved charge collection technologies and phonon timing information all should help minimize the surface-electron background and restore the full effectiveness of our discrimination technique for both Ge and Si. Once this has been accomplished, we expect to be limited by the cosmogenic neutron backgrounds at the Stanford site with an exposure of about 100-kg-d. To obtain this exposure we will instrument two silicon and four germanium devices with QET readout and six germanium devices with NTD readout, for a total of 200 g of silicon and 2 kg of germanium. Comparison of distributions from the Ge and Si will provide information on the backgrounds, especially neutrons. Multiple scattering of neutrons in the detector arrays will also provide a handle for background subtraction.

3 CDMS at Soudan

Ultimately, cosmogenic neutron backgrounds will limit the sensitivity of the experiment at the Stanford site. In order to take full advantage of these advanced detectors, we intend to continue the experiment at the Soudan Mine in northern Minnesota. The new CDMS II experiment would exploit the experience from CDMS I and utilize similar detector designs. The improved sensitivity will be obtained by fully-filling the cryogenic detector volume with CDMS detectors, increasing the active detector mass by an order of magnitude, and by operating CDMS II in the low background environment of the Soudan mine, which will decrease the cosmic ray induced background rates. The 2090 mwe overburden at Soudan attenuates cosmic-ray muons by some 5 orders of magnitude, which will greatly reduce cosmogenic activity in the apparatus and hence the neutron background.

Figure 4: Projections for CDMS reach in WIMP-nucleon cross section versus WIMP mass. The upper dotted line is where we would be right now at Stanford if we had a single 250 g Ge detector with the FLIP readout technology. The middle dotted line is the goal for CDMS-I at the Stanford site, with six 250 g Ge detectors. The bottom dotted line is the projection for Ge detectors at Soudan. The best current limits are shown for comparison along with the envelope of possible MSSM predictions (the peak corresponds to 3 events/(kg-day) for Ge).

Figure 4 shows our expected ultimate sensitivities for the Stanford and Soudan phases of CDMS. The Stanford curve is based on using six, 250 g Ge detectors with an exposure of 100 kg-days (CDMS I), ambient backgrounds of approximately 3 events/(keV-kg-day), and intrinsic background rejection of 99%. Following background subtraction, the resulting sensitivity is 0.01 events/(keV-kg-day) at the Stanford site, good enough to allow CDMS I to discover relic neutralino WIMPs over a significant part of the allowed parameter space. However, CDMS II at Soudan, with a total exposure of 10,000 kg-days, will improve on those limits by at least an order of magnitude. For spin-independent couplings, CDMS II will have better sensitivity than any other experiment for all but the lowest mass WIMPs, which seem to be ruled out by experiments at LEP. Of course, the hope is to obtain an unambiguous detection of WIMP dark matter sometime within the next few years!

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